MUlti-SpEctral, MUlti-SpEcies, MUlti-SEnsors (MUSES) Retrievals for "A Train", Suomi-NPP, and TROPOMI

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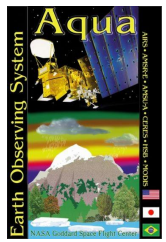
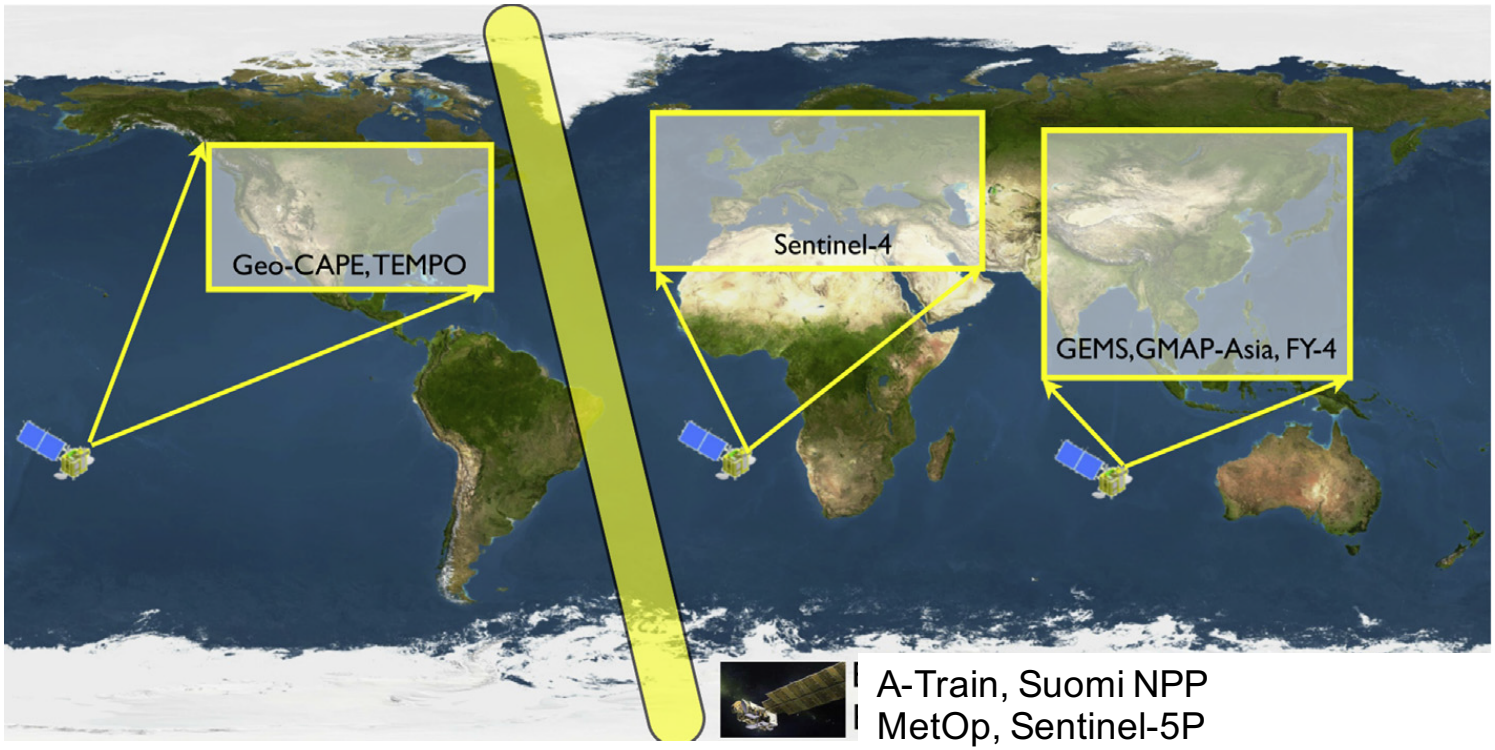


A new Atmospheric Composition Constellation to Observe Global and Regional Pollution and Greenhouse Gases

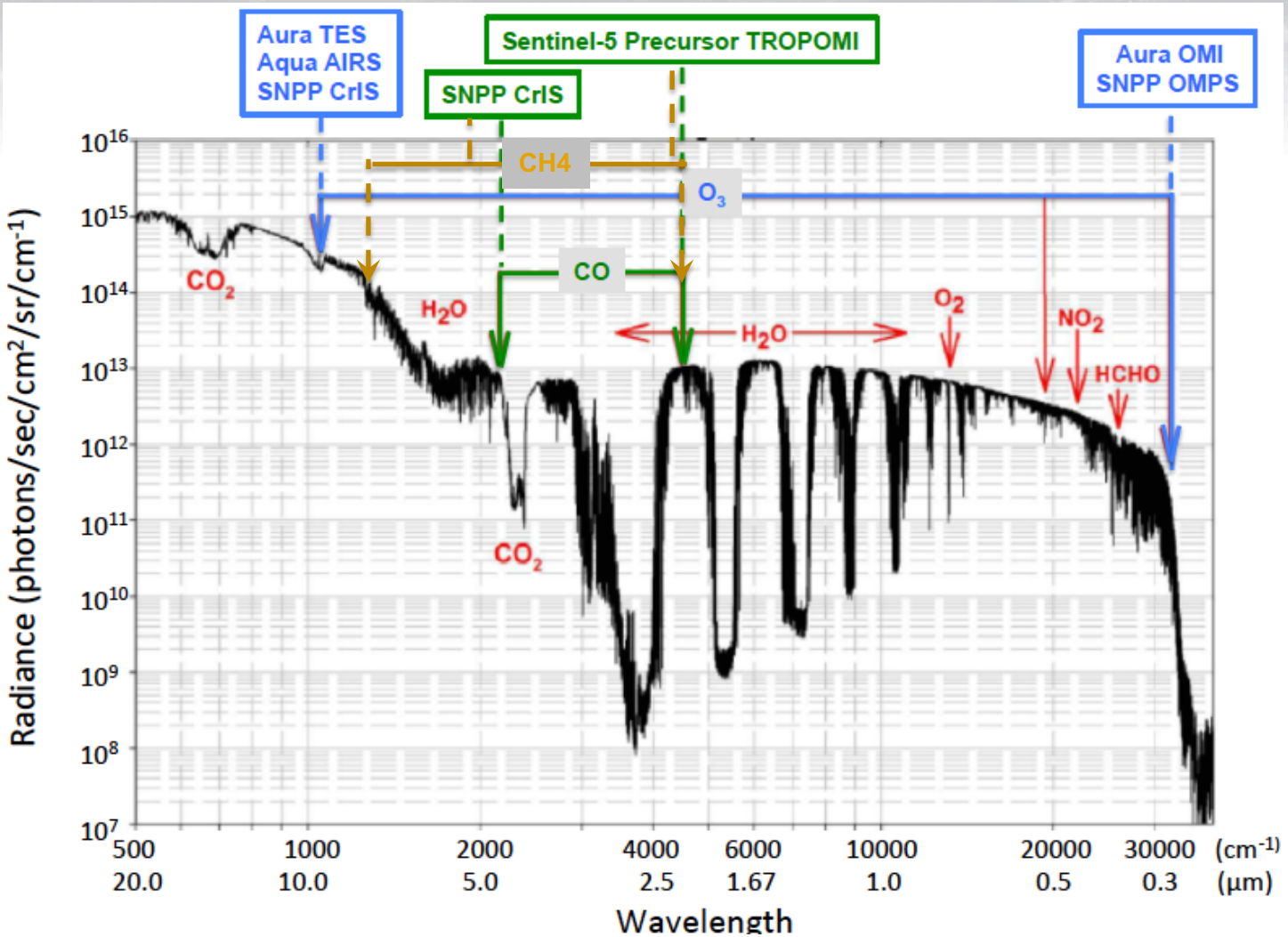
The rapid change in global emissions and their impact of air quality and climate requires a new observing system of GEO and LEO sounders to quantify global sources of local pollution and inferring surface carbon fluxes [Bowman, 2013; Fu *et al.*, 2016].

- LEO A-Train AIRS/OMI and SNPP CrIS/OMPS can support this constellation by distinguishing lower and upper tropospheric O_3 signals.
- LEO sounders will be a crucial link between GEO sounders over America, Europe and Asia as well as the sole satellite observations in the SH.
- LEO joint CrIS/TROPOMI measurements can provide the high resolution CO/CH_4 profile data [Fu *et al.*, 2016].



Adapted from Bowman, Atm. Env., 2013

Spectral Regions Used in Joint Retrievals



Measurements from TIR (LW) are sensitive to the free-tropospheric trace gases.
Measurements from UV-Vis-NIR (SW) are sensitive to the column abundances of trace gases.
Joint LW/SW measurements can distinguish upper troposphere from lower troposphere.

JPL MUSES Retrieval Algorithm

Multi-**S**pectra, **Mu**lti-**S**pecies, **Mu**lti-**Se**nsors (MUSES)

- Builds off of heritage from the Aura Tropospheric Emission Spectrometer (TES) optimal estimation (OE) algorithm to combine *a priori* and satellite data [Worden et al., 2007; Fu et al., 2013; Fu et al., 2015]

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \left[\mathbf{S}_a^{-1} + \underbrace{\mathbf{K}_{SW}^T \mathbf{S}_{\varepsilon\,SW}^{-1} \mathbf{K}_{SW}}_{SW} + \underbrace{\mathbf{K}_{LW}^T \mathbf{S}_{\varepsilon\,LW}^{-1} \mathbf{K}_{LW}}_{LW}\right]^{-1}$$

$$* \left[\mathbf{S}_a^{-1}(\mathbf{x}_a - \mathbf{x}_i) + \underbrace{\mathbf{K}_{SW}^T \mathbf{S}_{\varepsilon\,SW}^{-1}(\mathbf{L}_{SW} - \mathbf{F}_{SW}(\mathbf{x}))}_{SW} + \underbrace{\mathbf{K}_{LW}^T \mathbf{S}_{\varepsilon\,LW}^{-1}(\mathbf{L}_{LW} - \mathbf{F}_{LW}(\mathbf{x}))}_{LW}\right]$$

Key characteristics

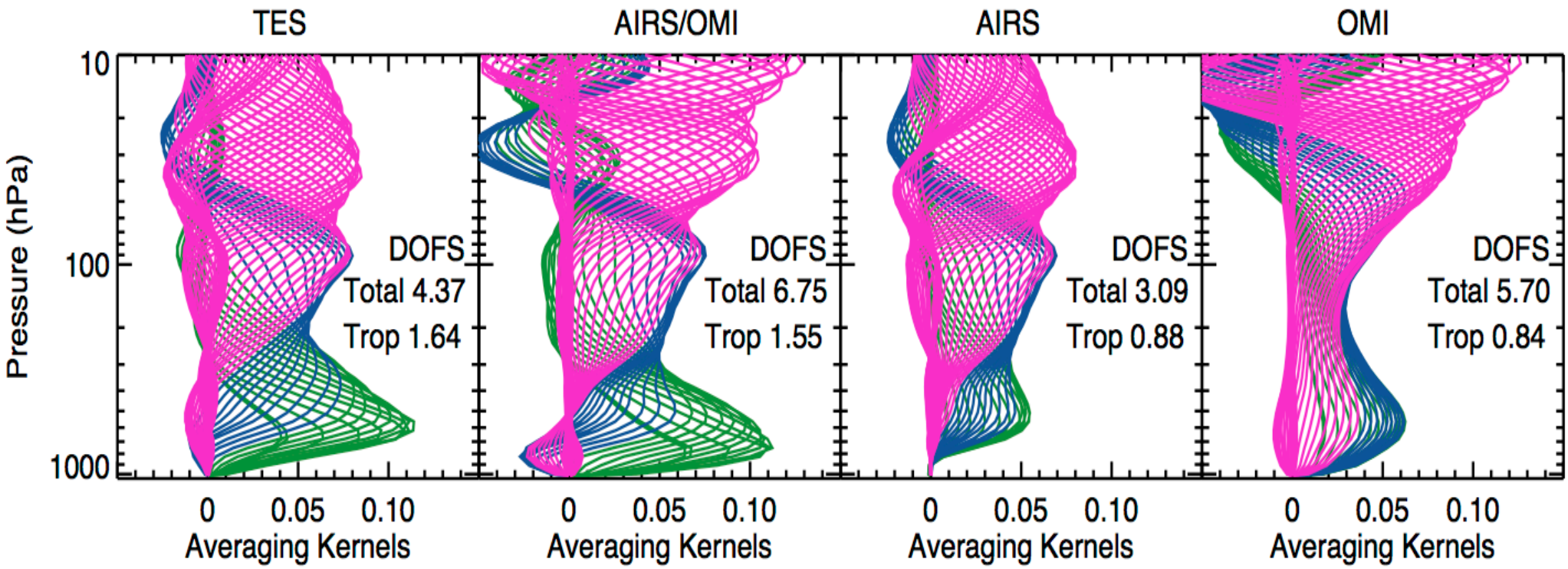
- Use common a priori **X**a and **S**a
- Instrument specific precision $\mathbf{S\varepsilon}_{LW}$, $\mathbf{S\varepsilon}_{SW}$
- Forward model (**F**) and Jacobians (**K**) for LW and SW sensors
  - Clouds, surface property
  - Instrument response function

Sample Averaging Kernels and Estimated Uncertainty

- MUSES provides observation operator (H) needed for data assimilation

$$H(x) = x_a + \mathbf{A}(x_{model} - x_a)$$

- Averaging kernel matrix (A) is the sensitivity of the retrieved state to the true state.
- The trace of averaging kernel matrix is the degree of freedom for signals (DOFS).

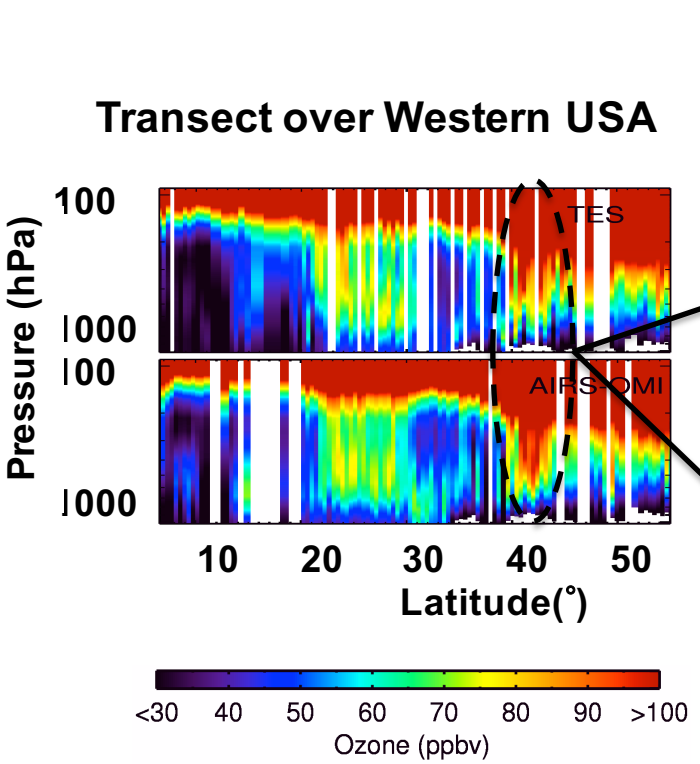


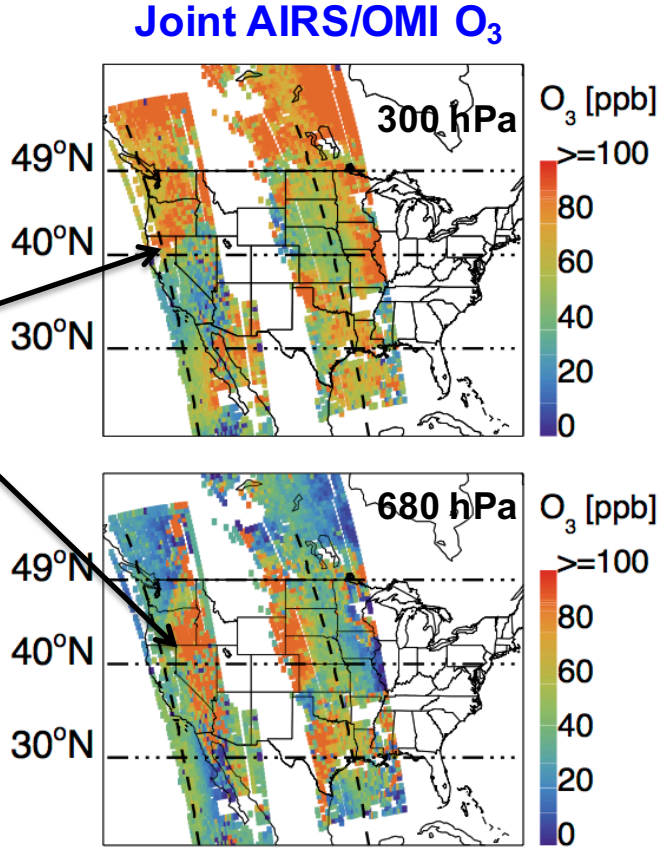
Joint AIRS/OMI and TES observations on August 23, 2006 during TexAQS Aircraft Flight Campaign

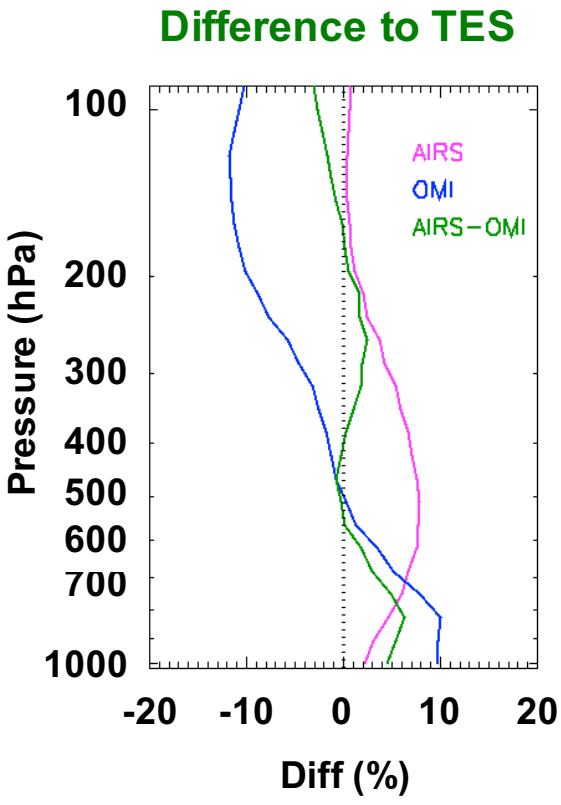
TES O_3, AIRS/OMI O_3, AIRS CO and cloud retrievals on August 23, 2006 during TexAQS aircraft flight campaign have been processed using common MUSES algorithm.

Joint AIRS/OMI ozone retrievals

- Differ from the *a priori* profiles
- Show best agreement to TES, in comparisons to each instrument alone

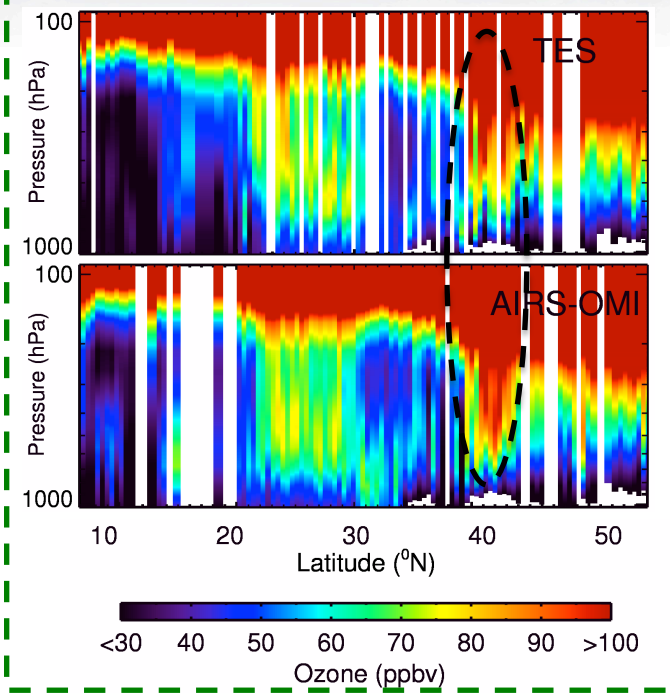




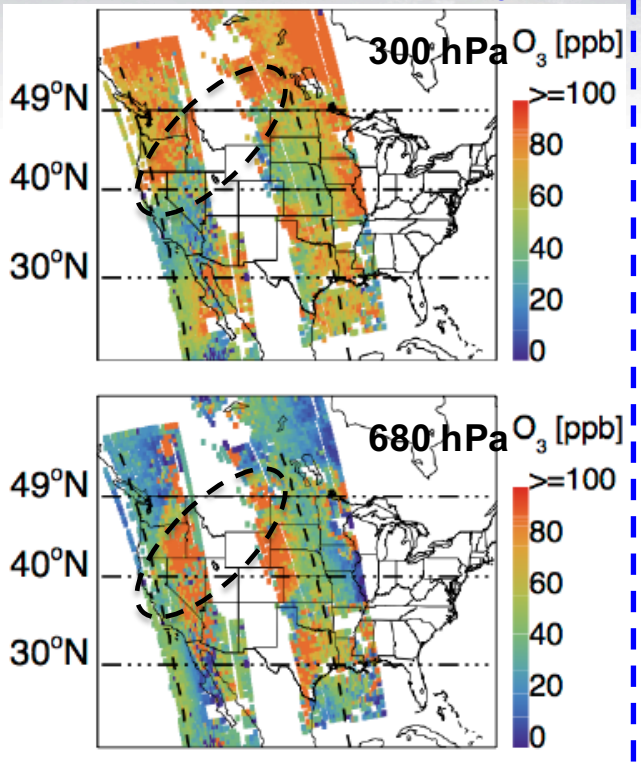


Impact of Biomass Burning on Ozone Distribution on August 23, 2006 during TexAQS Aircraft Flight Campaign

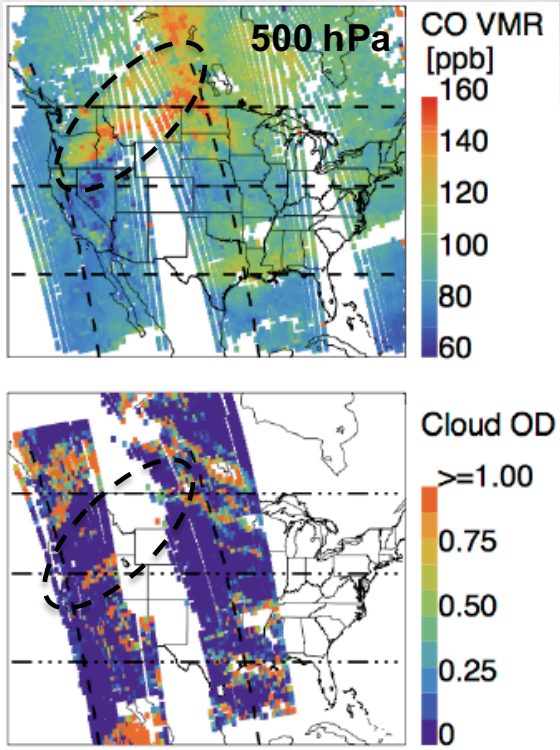
Collocated TES & Joint AIRS/OMI O_3 Measurements over Western USA



Joint AIRS/OMI O_3



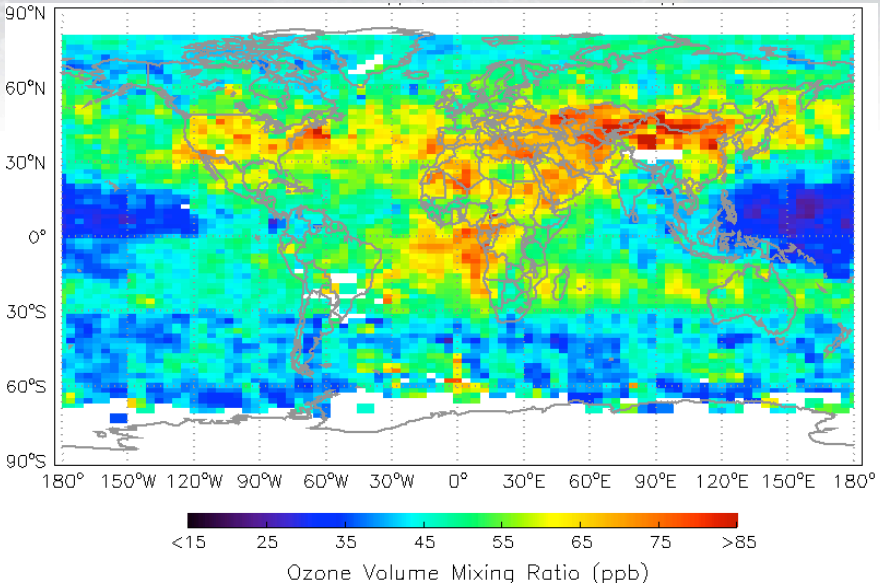
AIRS CO and Cloud



- The enhanced ozone at 680 hPa is collocating to the enhanced CO due to the fire emissions.
- Joint AIRS/OMI retrievals distinguish the amount of O_3 between lower and upper trop, similar to TES, with broader spatial coverage, which helps in distinguishing between stratospheric influences and biomass burning.
- MUSES has been extended to additional species (NH_3, CH_3OH, HCOOH, CH_4, PAN) using measurements from multiple space sensors (TES, AIRS, CrIS, OMI, OMPS, TROPOMI).

Monthly Mean Ozone Global Maps

Joint AIRS/OMI



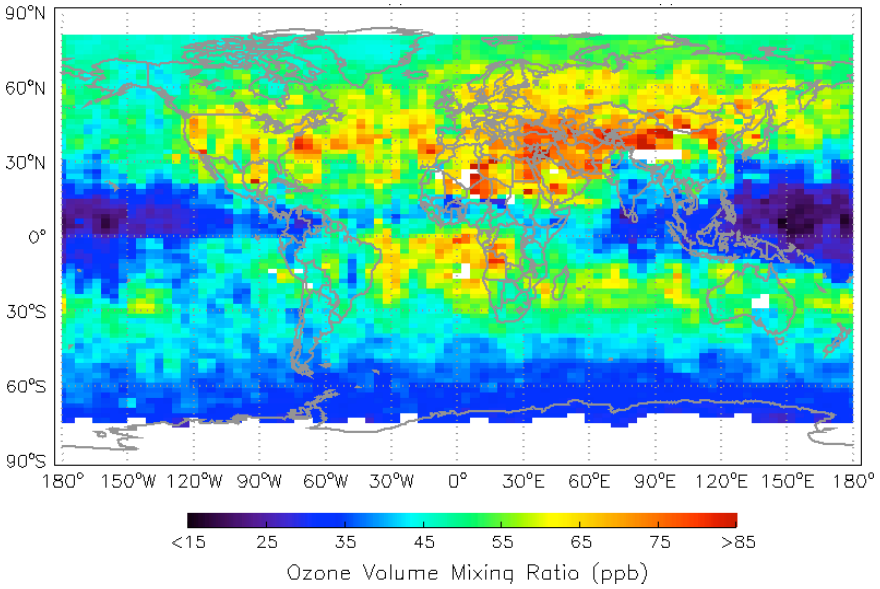
The JPL $(MS)^3$ has been implemented and applied to joint AIRS/OMI ozone retrievals over global scale

- August 2006

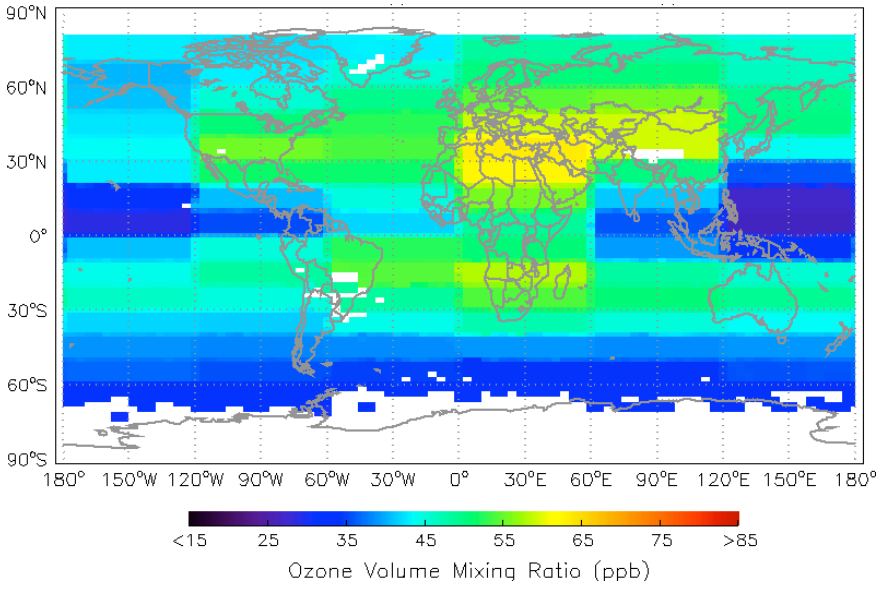
Characteristics

- Differ from *a priori*
- Both TES and Joint AIRS/OMI show similar spatial patterns, e.g., capturing the enhanced ozone over the continental outflow and biomass burning active regions

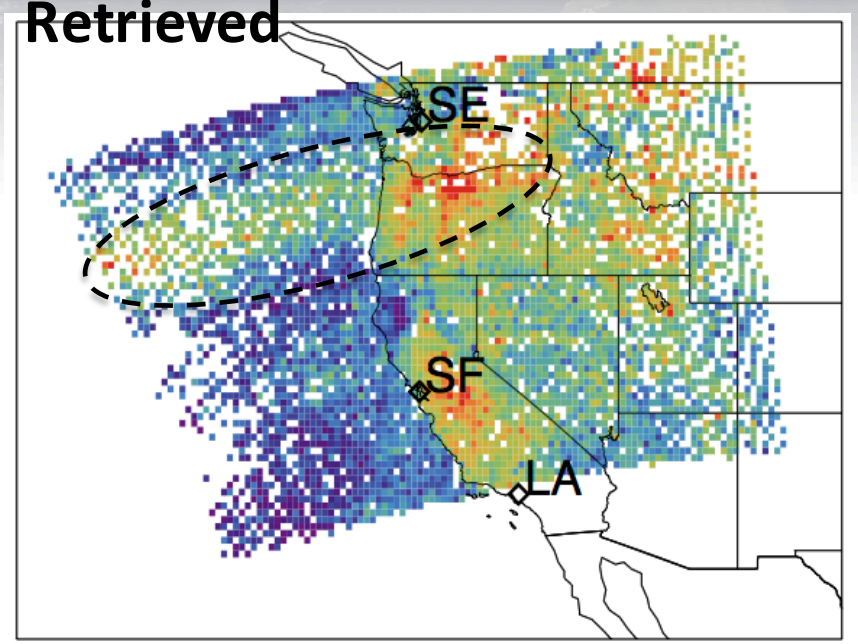
TES

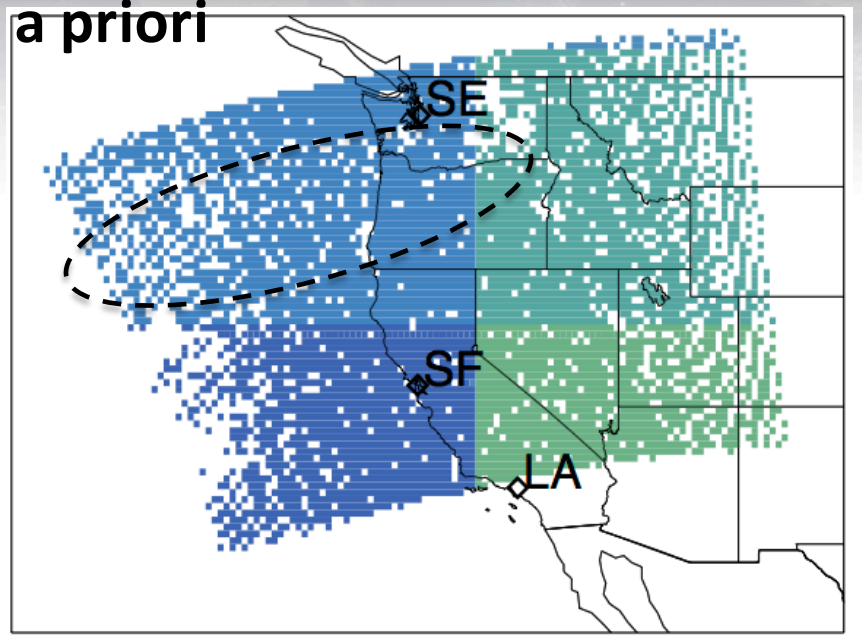


a priori

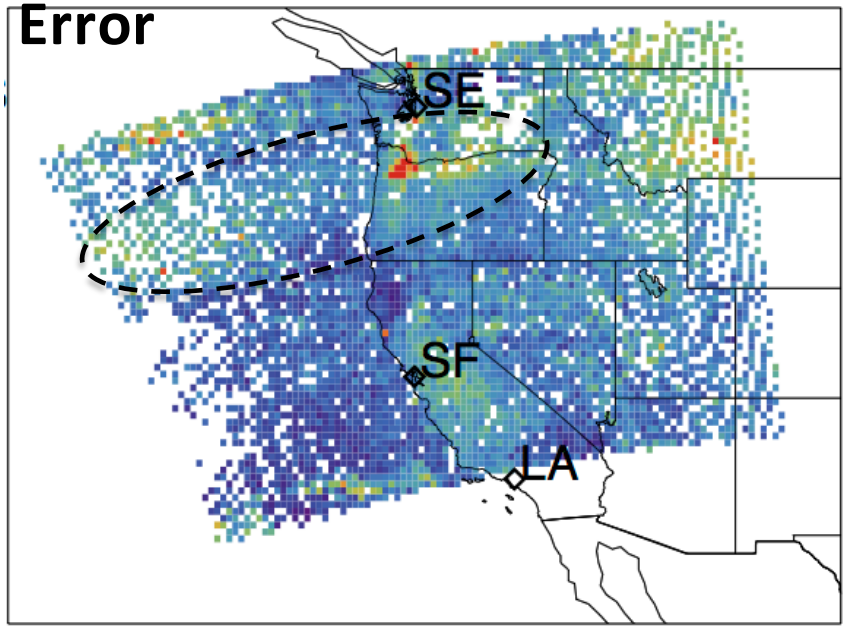


Retrievals Using MUSES Algorithm and SNPP Measurements in Support of the coming NOAA FIREX Intensive Campaign





O_3 VMR
[ppb]
80
70
60
50
40



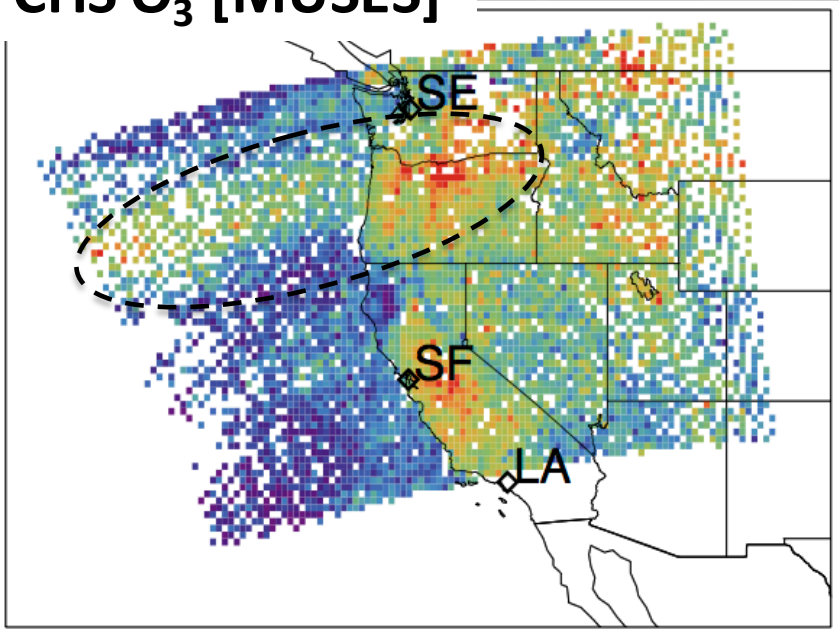
O_3 VMR
[ppb]
2.00
1.50
1.00
0.50

CrIS O_3 retrievals using MUSES

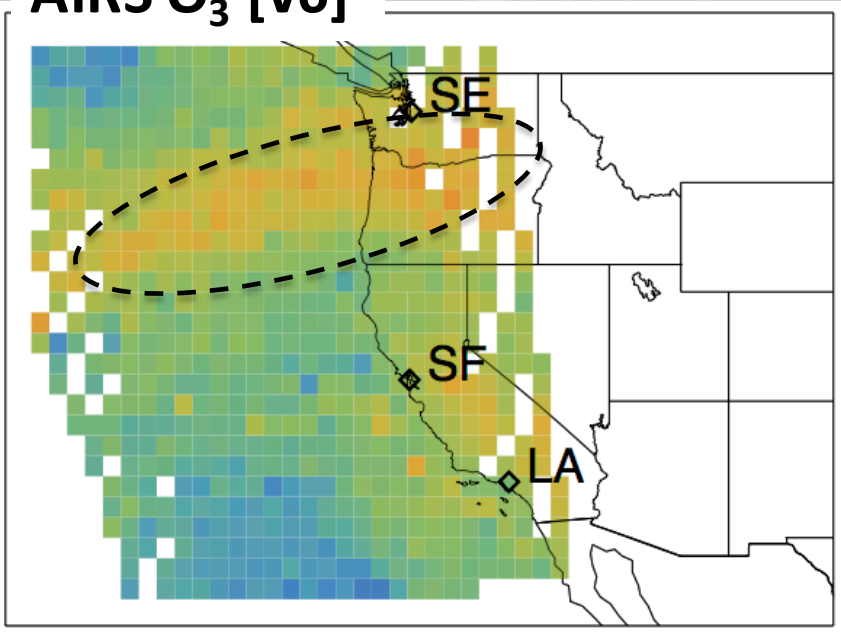
- August 19, 2015
- Single footprint (14 x 14 km^2 at Nadir)
- Full spectral resolution (0.625 cm^{-1})
- Provides observation operator (H) needed for data assimilation
- Cloud OD <= 1.0

Observations from AIRS, CrIS and MODIS on Aug 19, 2015

CrIS O_3 [MUSES]



AIRS O_3 [v6]

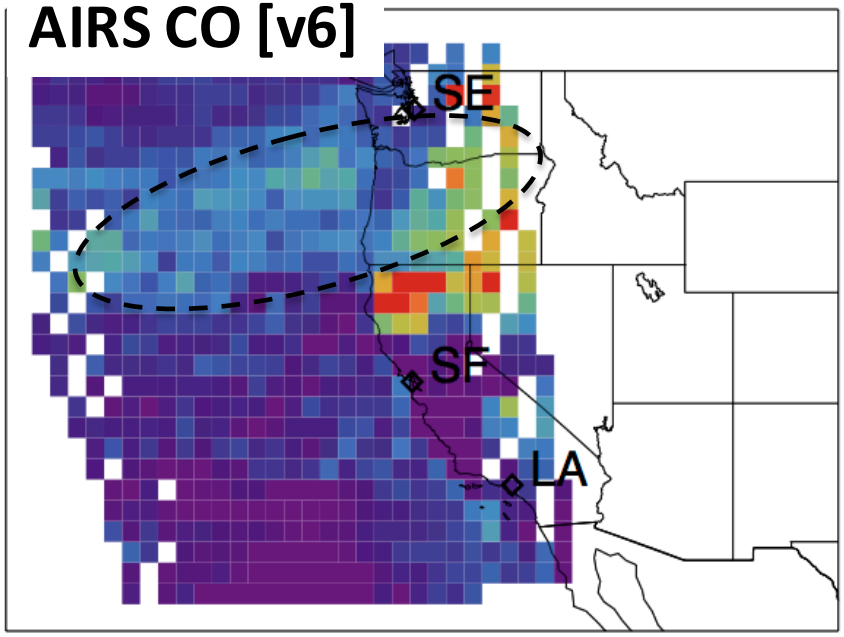


O_3 VMR

[ppb]

80
70
60
50
40

AIRS CO [v6]

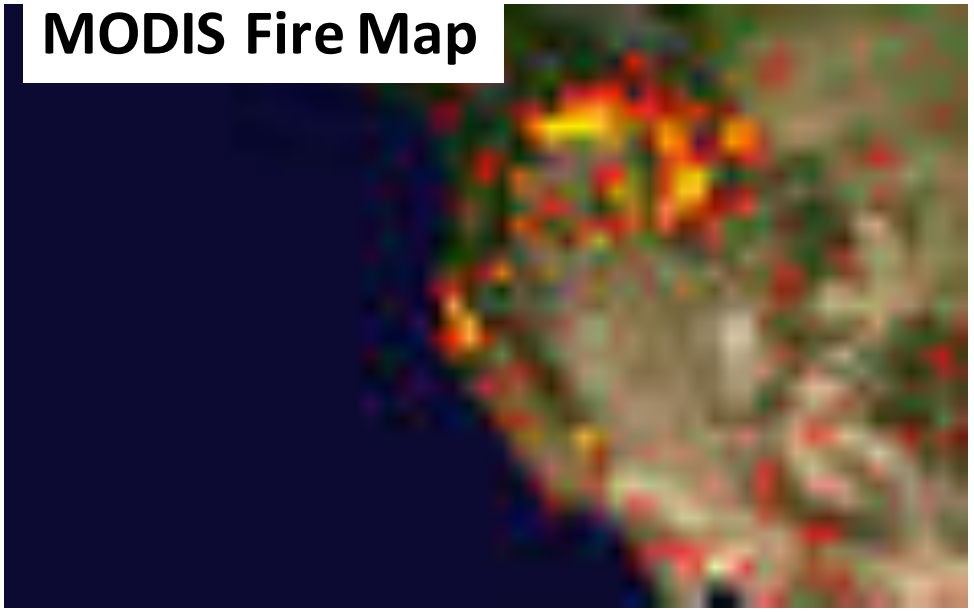


CO VMR

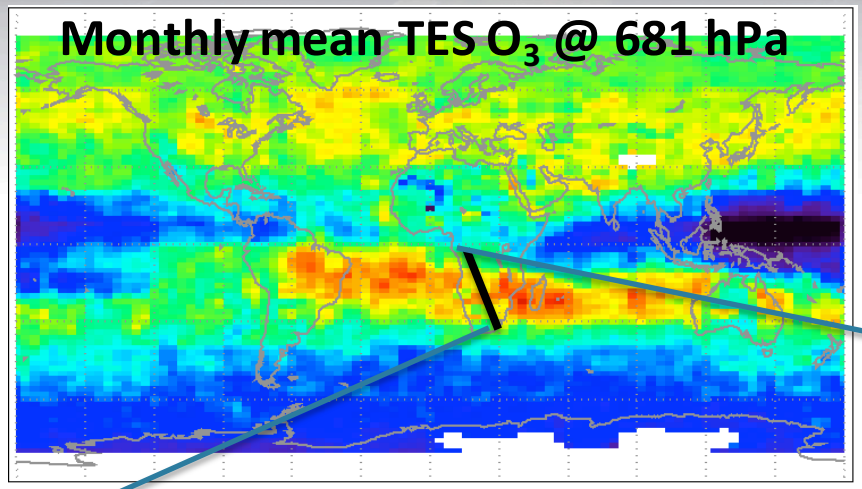
[ppb]

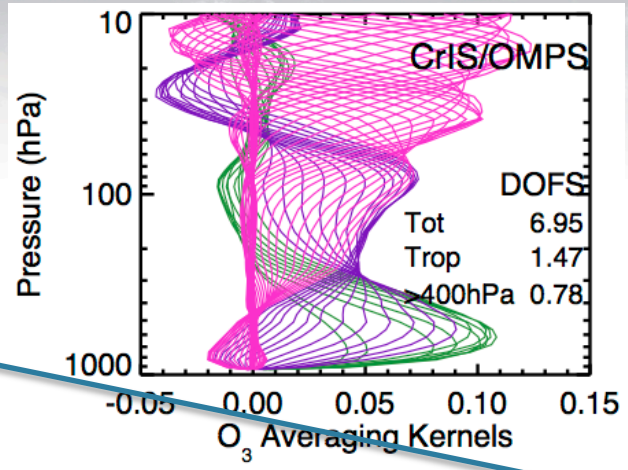
180
160
140
120
100
80

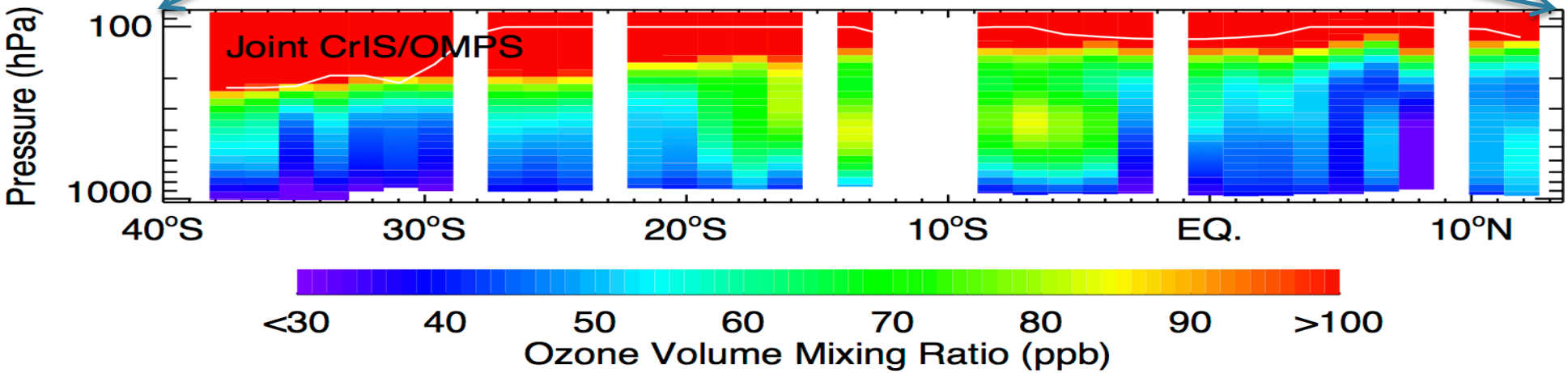
MODIS Fire Map



Extension to Joint CrIS/OMPS O_3 Retrievals





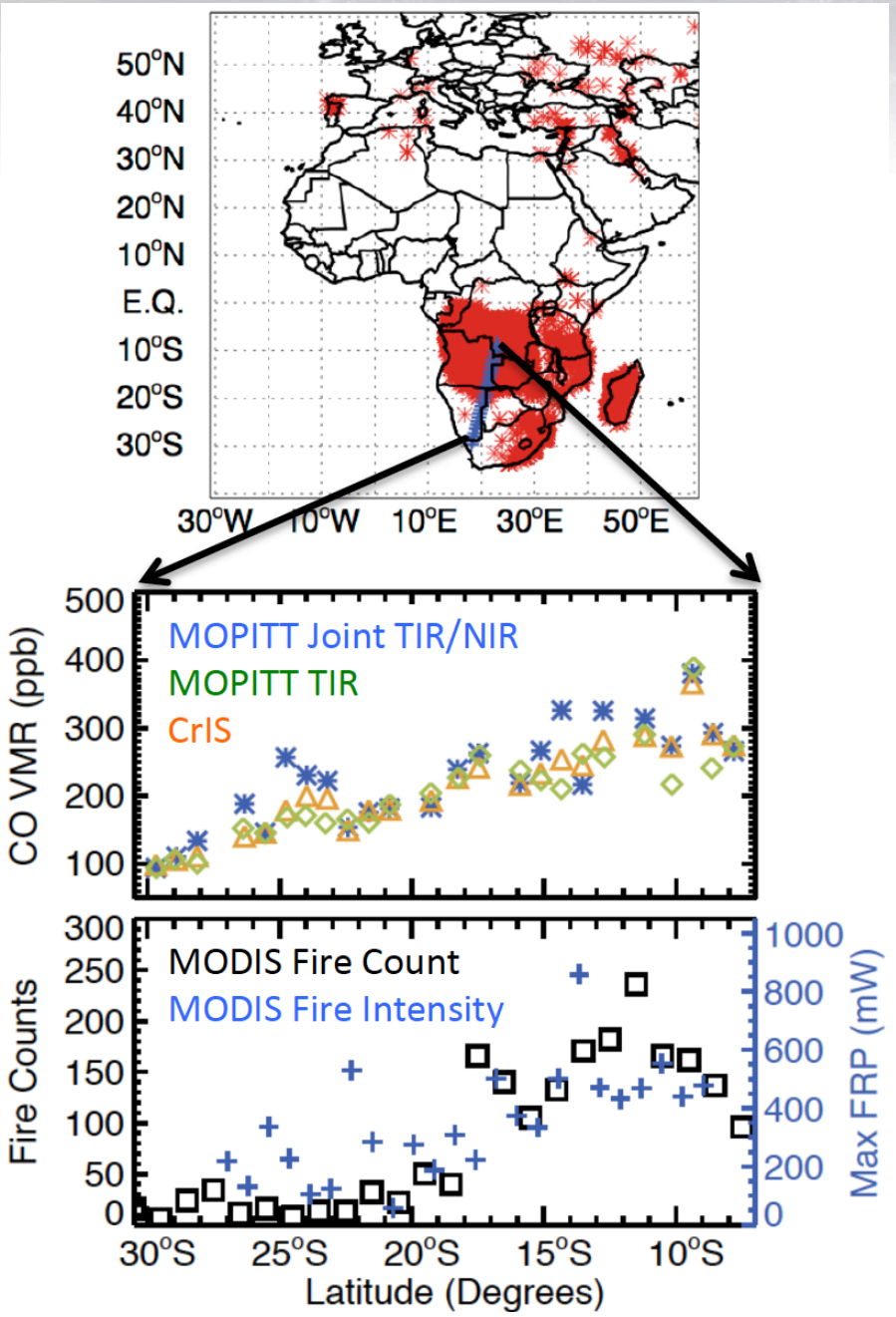


- MUSES has been applied to joint CrIS/OMPS ozone retrievals over Africa on October 21, 2013.
- The elevated ozone concentrations between 2 - 20° S are associated with biomass burning.
- Joint CrIS/OMPS O_3 and CrIS CO retrievals using MUSES will support the NOAA FIREX flight campaign (Fire Influence on Regional and global Environments Experiment) – an intensive study of the impacts of western North America fires on climate and air quality.

CrIS and MOPITT CO during Biomass Burning on August 27-28, 2013

Motivation: MOPITT's unique thermal IR/near IR multispectral CO measurements, which are able to separate near-surface from the free troposphere, have no planned follow-on.

We applied the MUSES algorithm to the retrieval of CO VMR profiles from the NOAA/NASA CrIS Measurements. An analysis showed that combining CrIS TIR with the Sentinel 5p TROPOMI NIR data would have comparable to vertical sensitivity of MOPITT but with daily coverage (Fu *et al.*, 2016).

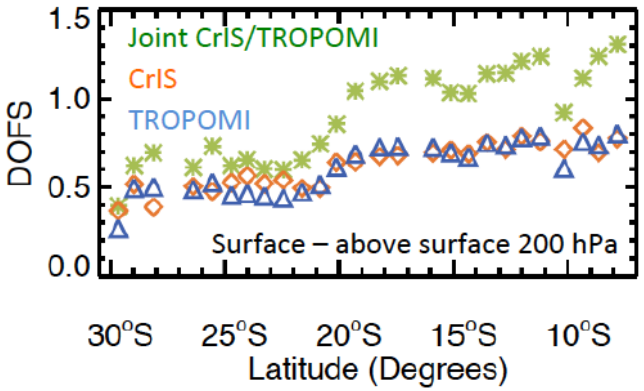


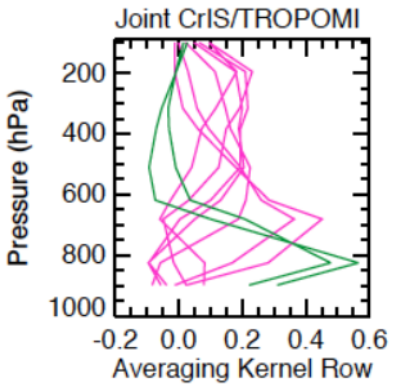
MOPITT and CrIS

- Real CrIS single footprint, full spectral resolution measurements
- MUSES algorithm was used in

Joint CrIS/TROPOMI

- Synthetic retrievals with realistic conditions
- MUSES algorithm

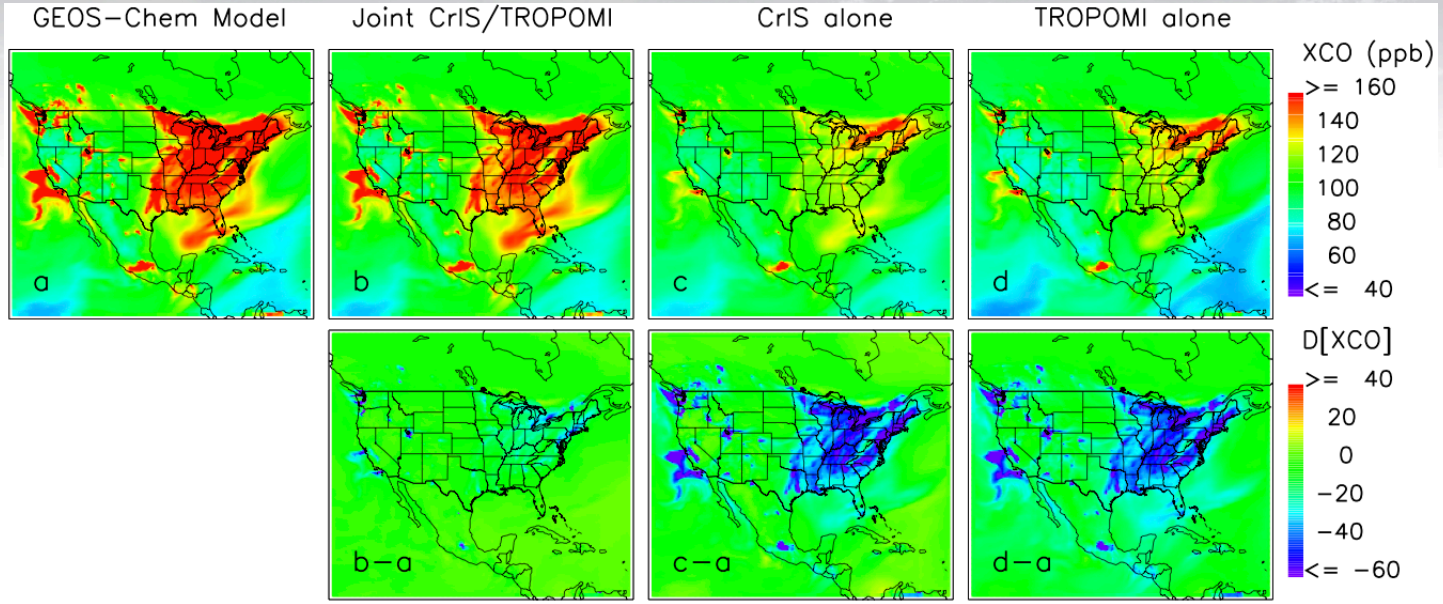




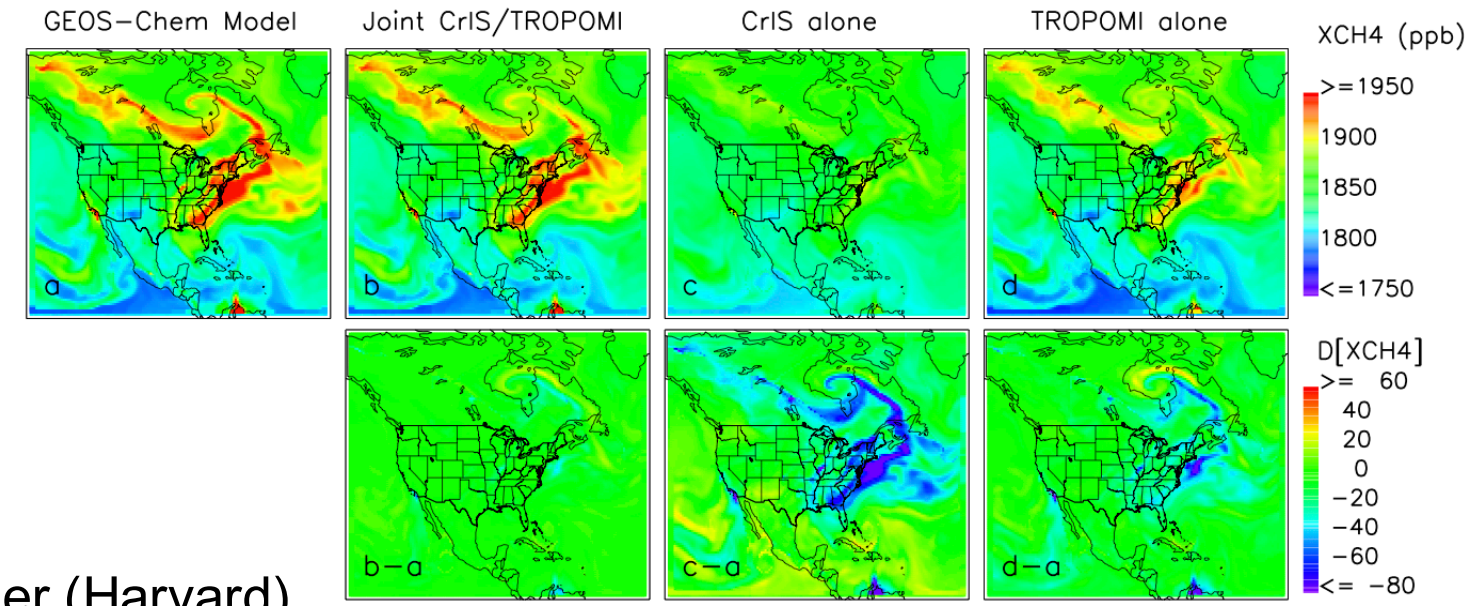
High Resolution CO/CH_4 Profile Data Through Combining TROPOMI/CrIS Measurements

Joint CrIS/TROPOMI retrievals could lead to

- Extend and improve the MOPITT joint TIR/NIR **CO** data



- Extend and Improve the joint TES/GOSAT **CH_4** data



GC run courtesy A. Turner (Harvard)

Summary

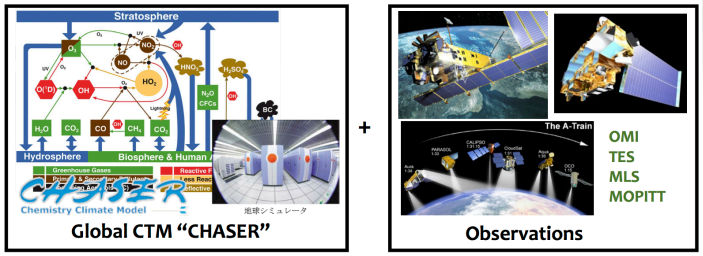
- The scientific objectives and societal impacts of Aura are as relevant as ever
  - No obvious follow-on to Aura
  - Community focus has been on geostationary observations, e.g., GEO-CAPE, TEMPO, GEMS
  - Critical need to assess the potential of "committed" LEO sounders to continue Aura (and other EOS) observations
  - Decadal survey missions should be considered in light of that potential.
- MUSES retrieval algorithm can combine radiances measured from LW and SW sensors including TES, AIRS, CrIS, OMI, OMPS, TROPOMI.
  - Joint AIRS/OMI and CrIS/OMPS retrieved ozone profiles meet TES ozone vertical accuracy but surpass spatial coverage.
  - Joint CrIS/TROPOMI retrieved carbon monoxide profiles show similar vertical resolution as MOPITT TIR/NIR, but with a factor of two finer footprint size and daily global coverage.
- The optimal estimation approach of MUSES provides observation operators and characterization of joint data products needed for data assimilation.
- These observations have the potential to be the pillar of an international air quality constellation [Bowman, 2013].

Backup

Data Assimilation System of the NASA A-Train Observations

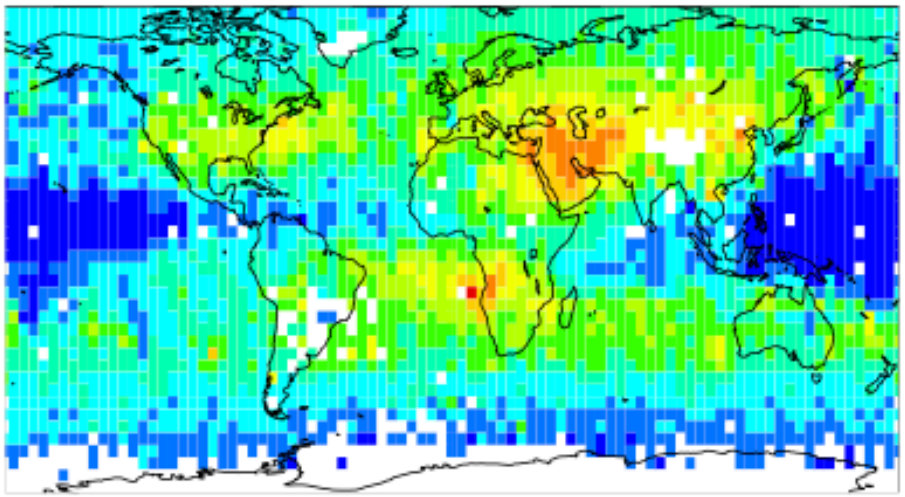
- MUSES algorithm delivered joint AIRS/OMI ozone and observation operator that enable data assimilation, e.g., the CHASER-DA.
- Assimilations of AIRS/OMI ozone leads to enhanced concentration over middle east and south Africa.
- Consistent to the previous study of the summertime buildup of tropospheric ozone abundances over the Middle East [Liu et al. 2009]

- Dr. Kazuyuki Miyazaki, implemented the CHASER data assimilation system.

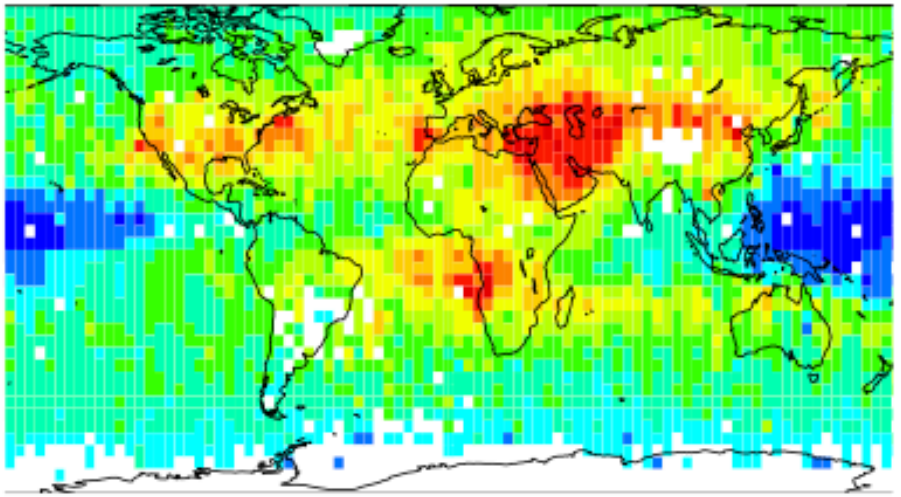


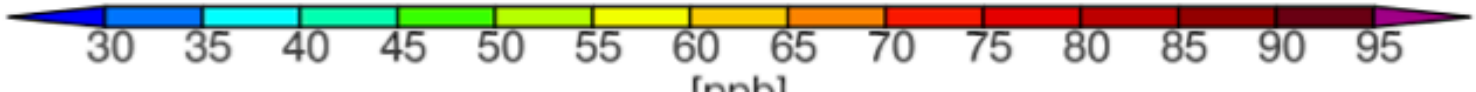
Miyazaki, 2009; Miyazaki et al., 2011, 2012a, 2012b, 2013, 2014, 2015

CHASER CTM Prediction



Data Assimilation Combined AIRS/OMI and CHASER





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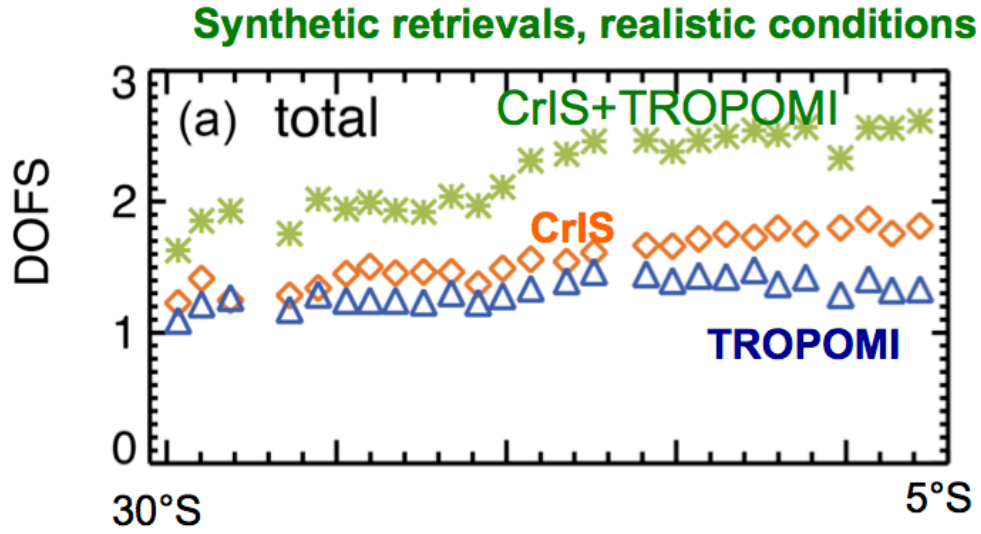

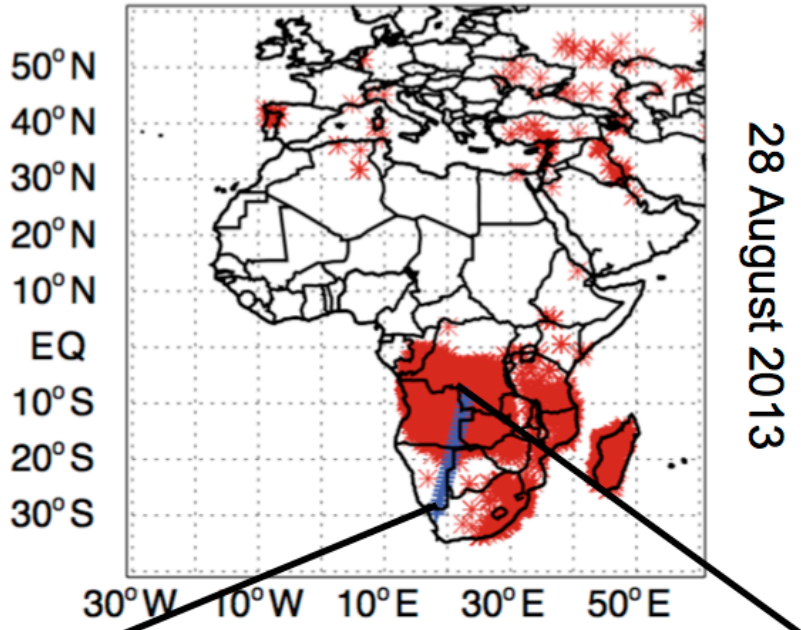

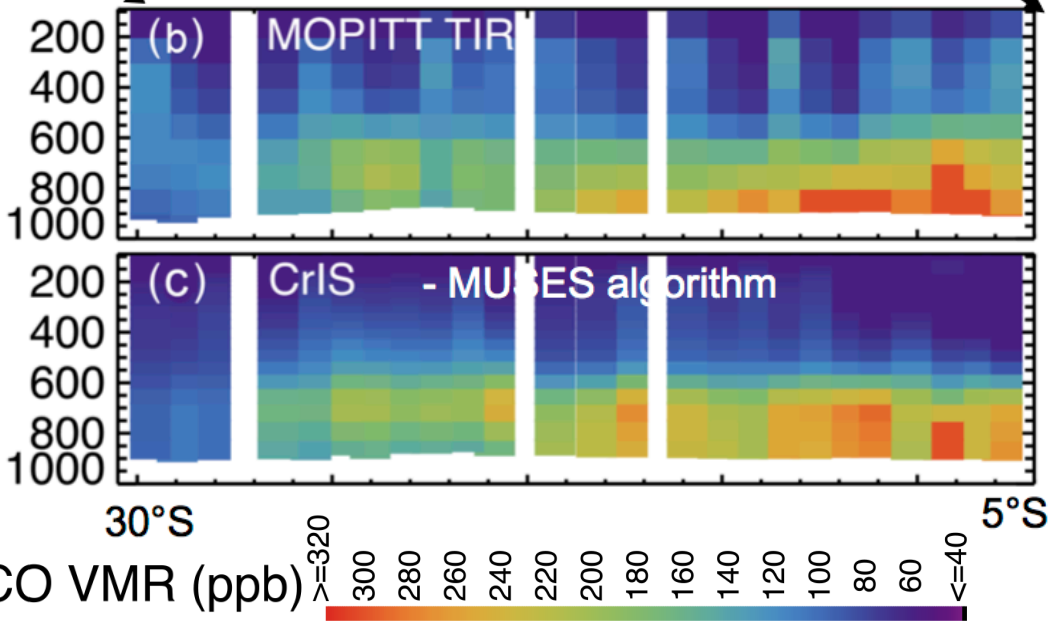

Monthly O_3 Global Maps – towards Providing Decade Long Global Ozone Profiles

The JPL MUSES has been implemented and applied to joint AIRS/OMI ozone retrievals over global scale. We are processing June to August 2006 data.

Characteristics (e.g., August 2006)

- Both TES and Joint AIRS/OMI show similar spatial patterns, e.g., capturing the enhanced ozone over the continental outflow and biomass burning active regions
- Differ from *a priori*